TiGER: Tiny bandwidth key encapsulation mechanism for easy miGration based on RLWE(R). *

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Abstract. The Quantum Resistant Key Encapsulation Mechanism (PQC-KEM) design aims to replace cryptography in existing security protocols. If PQC-KEM is faster and lighter than ECDH or DH, it will allow easy migration to existing security protocols. However, this is considered impossible due to the nature of the safe fundamental problem in the quantum environment. In particular, ciphertext size and public key size larger than RSA or ECC are important issues. Therefore, it is necessary to design a scheme with the smallest possible ciphertext and public key size. We propose TiGER, an IND-CCA secure KEM based on RLWE(R). TiGER has 1,408 bytes ciphertext and 928 bytes public key at AES256 security level. Compared to KYBER (ciphertext and public key sizes 1,568 bytes each at AES256 security level), which exceeds Ethernet's MTU of 1,500 bytes, TiGER is expected to be advantageous regarding actual network utilization.

Keywords: Post quantum cryptography migration · Ring learning with error (RLWE) · Ring learning with rounding (RLWR) · Key encapsulation mechanism (KEM)

1 Introduction

PQC-KEM (Post Quantum Cryptography Key Encapsulation Mechanism) must be easily migrated to legacy security protocols ((D)TLS, IKE, SSH, IPSEC, etc.), and performance, device memory, and communication bandwidth must be similar to current KEM such as ECDH and DH for migration.

Analyzing the algorithms submitted to the NIST competition, choosing the Lattice problem for migration seems reasonable. The KEM based on LWE and its variants (Ring/Module LWE(R)) is fast, so it does not constrain migration. However, KEM based on LWE and its variants are unsuitable for the resource

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constraint device and communication bandwidth because the size of the public key, private key, and ciphertext are more significant than that of DH or ECDH, which are legacy KEM. In this respect, The NIST competition also used the size of the public key and the size of the ciphertext as principal evaluation factors. Intuitively, structured RLWE(R) can have smaller bandwidth and efficient performance than less structured MLWE(R). Nevertheless, the bandwidth and operation speed of the RLWE(R) algorithm submitted to the NIST competition were comparable to those of MLWE(R)-based `KYBER` or `SABER`, so they were all rejected. However, we understand that NIST's first chosen KEM standard, `KYBER`, is a bit unsuitable for legacy security protocols. The bandwidth of Ring/Module LWE(R) cannot be as small as DH and ECDH, but migration is much easier when the fragmentation can be avoided in the network. In the Ethernet environment, the MTU (Maximum Transmission Unit) is generally 1,500 bytes, so it is advantageous if the size of the public key and ciphertext exchanged during the KEM process is smaller than 1,500 bytes. In the NIST PQC competition, AES128, AES192, and AES256 security strengths were all designed, but CNSA2.0 recommended AES256 security strengths parameters. However, the public key and ciphertext sizes of `KYBER1024` with AES256 security strength are each 1,568 bytes, so they exceed the MTU of Ethernet. They may require complex implementation.

We propose TiGER a compact IND-CCA secure KEM based on RLWR and RLWE where the public key and the ciphertext size do not exceed 1,500 bytes on all parameters. TiGER generates a public key based on RLWR, generates a ciphertext based on RLWE, and compresses it to achieve small bandwidth. RLWE(R) are structured lattices, but specific attacks that apply only to these are unknown and have been well-studied for a relatively long time. Also, we choose the RLWE(R) modulus $q = 256$ to cut-off a bandwidth. Since the hardness of RLWE(R) is determined by the dimension n and the σ/q, where σ is the standard deviation of noise distribution, choosing a small q is not a harmful hardness if determining a proper noise distribution [29,23]. If an error is added to a small q and even ciphertext compression is performed, the decryption failure rate will be very high. We solve this problem with error correction codes `XEf` [9] and `D2` [7]. In particular, the unique characteristics of the ring $f(X)=X^n + 1$ in $R_q := \mathbb{Z}_q[X]/(f(X))$ are a good combination with the error correction code. That is, in the $X^n + 1$, n is constrained to the power of 2, and since it is sufficiently more significant than the required message size (128, 192, 256 bits), this buffer is used as a valuable space for redundancy bits. We use a sparse ternary uniform distribution with hamming weights for the secret/error distribution. It chose to enjoy being able to fine-tune the standard deviation through hamming weights while minimizing the propagation of errors. As constraints n and fixed q, parameters that are challenging to handle can be supplemented with hamming weights. It also allows to replace polynomial multiplication with bit-wise operations.

As a result, TiGER have the size of the ciphertext and public key is smaller than 1,500 bytes each, so it can easily migrate to the legacy security protocol.

1.1 Design rationale

TiGER is an IND-CCA-secure Key Encapsulation Mechanism (KEM) based on the hardness of solving the learning-with-rounding and learning-with-errors problem over Ring lattices (RLWR and RLWE problem). The TiGER scheme is constructed in two-steps: we first introduce and IND-CPA-secure PKE(Public Key Encryption) scheme encrypting messages of a length of 16 or 32 bytes. We then use a Fujisaki–Okamoto (FO) transform by Jiang et al. [19] to construct the IND-CCA-secure KEM.

Choice of the Ring We use $f(X)=X^n+1$ in $R_q := \mathbb{Z}_q[X]/(f(X))$, where n is the power of 2. It is the common choice used by most of the Ring-lattice submitted to NIST competitions. The common ring has the advantage in that the polynomial modular reduction operation is straightforward, and there have been no known attacks exploit it [22]. On the other side of this choice, $f(X)=X^{n+1}+1$ in [9], where $n+1$ is prime and $f(X)=X^n-X^{n/2}+1$ in [28], where $n=2^a3^b$(a and b are positive integer) have the flexibility to select the appropriate degree n for each security level. Although we observed these recent studies meaningfully, we decided to enjoy the aspect of conservative security that there was no particular weakness even though $f(X)=X^n+1$ was well studied and the attribute of making the probability of decoding error the smallest. In addition, the constraint of degree n is tricky to witness as a disadvantage because it provides a valuable buffer space in terms of employing the error correcting code.

Choice of modulus All integer modulus in the scheme are power of 2. It improve performance by replacing $\lfloor (p/q) \cdot \mathbf{x} \rceil$ with ADD and AND operations [13]. Especially, fixed $q = 256$ is a byte size. The first proposed the choice of modulus q below the byte size with $q = 251$ in `LAC` [23], which won the PQC competition in china. In addition, `LizarMong` [20] designed the scheme with $q = 256$, which is the power of 2 like ours, and then LAC also added $q = 256$ parameter as an option during the NIST competition. Intuitively, this choice enjoys a small bandwidth and improved performance. It also provides very efficient modulo operation and memory usage and is suitable for single instruction multiple data (SIMD) implementations such as AVX2 and NEON. Even though the modulus is small, it can not affect the security since we maintain the error rate by selecting proper error distribution [23,29]. The modulus p used for RLWR and the modulus k_1, k_2 used for ciphertext compression are also the power of two.

Distribution We use a sparse ternary secret with a hamming weight [13] and [9] proved the hardness of the sparse ternary secret variants RLWE(R). Multiplication of sparse ternary secret polynomials can be replaced with bit operation to improve performance [2,22]. It also maintains correctness by preventing decryption errors from increasing and can select the optimized standard deviation for each security level by finely adjusting the hamming weight and has the advantage of having resistance to high hamming weight attacks [23] that manipulate the centered binomial distribution.

Adopt error correction code $R_q := Z_q[X]/X^n + 1$ constrains n to the power of 2, so choose $n = 512$ or $n = 1024$ depending on the security level. Since general RLWE(R) schemes map one bit message to one coefficient in R_q, n is larger than the required size of the shared key (128, 192, 256 bits). We claim that RLWE(R) has the best compatibility with error correcting code (ECC) regarding message processing. A redundancy bit is inevitably required for error correction. n larger than the length of the shared key can be used as a buffer sufficient to use the redundancy bit. In particular, Because the RLWE(R) is a variant to maximize performance and reduce the size(ciphertext, public key) of the LWE, RLWE(R) with comparable performance and size to less structured MLWE is meaningless [4]. Thus, a small q selection is needed in RLWE(R), increasing the decoding failure probability. So, the combination of RLWE(R) and ECC is beautiful because ECC can be an excellent choice to overcome these drawbacks. We use the well-studied `XEf` [9] and `D2` [7] to utilize the buffer space. Since `XEf` avoids table look-up and branch conditions, it resists timing attacks [9]. That is, a 256-bit message is encoded with `XE5` to make a 512-bit code word (234 redundancy bits and 22 padding bits), and `D2` encodes the code word to make a 1024-bit $\hat{\mathbf{M}}$. Decoding is in reverse order.

Compress Public-key and Ciphertext NIST's candidate algorithms commonly use compression techniques. Public-key compression means sending only the *Seed* instead of $\mathbf{a}$ in R_q, and the receiver recovers $\mathbf{a}$ using the hash function. This reduces the public-key size from $2n \log q$ to size-of-$Seed$ $+ n \log q$. Ciphertext compression is similar to the RLWR idea of discarding a few LSBs in $\mathbf{c_1}$, $\mathbf{c_2}$. IND-CCA KEM also can do the same. Ciphertext compression affects the security strength and decryption failure rate of the scheme. See subsection 5.4 and subsection 3.5 for an analysis.

1.2 Advantages and limitations

1.2.1 Advantages

- **Compact :** TiGER has the smallest[1] ciphertext and public key size among the LWE (include variants) algorithms that round3 of the NIST competition. That is a natural result since we chose a small coefficient $q = 256$, generated the public key RLWR, and compressed the ciphertext that made by RLWE.
- **Easily migration :** Our goal in designing PQC-KEM is to replace key exchange algorithms in security protocols such as (D)TLS, IKE, SSH, IPSEC, and DNSSEC. We claim that if the public key or ciphertext size is more significant than 1,500 bytes(Ethernet MTU), migration to existing security protocols may be complexed. TiGER is the IND-CCA KEM with a ciphertext and public key size smaller than 1,500 bytes at the AES256 security level.
- **High performance :** TiGER samples the secret $\mathbf{s}$ and the noise $\mathbf{e}$ from a sparse ternary uniform distribution, making polynomial multiplication sim-

[1] Evaluating the IND-CCA secure scheme with security level 5

ple and efficient. Furthermore, since all moduli are a power of 2, we do not require explicit modular reduction.

- **Friendly for SIMD :** TiGER is friendly for SIMD, such as AVX2 and NEON, due to the modulus q=256 (8 bits). For example, C intrinsic data types `_m256i` can be stored in a 32-dimensional 8-bit integer so that only 16 `_m256i` data types can express TiGER parameters.

1.2.2 Limitations

- Side-channel analysis attack surface is larger than Non-ECC. However, we believe that side-channel attacks will be solved with time and the wisdom of crowds(as in the case of RSA and ECC). The `XEf` resists timing attacks[32]. Some attacks assume more powerful attackers, but we firmly believe that the respected cryptography community will solve them.
- Although RLWE and RLWR have proven hardness and have been studied for longer than MLWE(R), their security is questioned because they are structured lattices. However, there are no known attacks in RLWE and RLWR, and RLWE is well-studied because of the homomorphic encryption, so there is no doubt about it.

2 Preliminaries

2.1 Public Key Encryption

A public key encryption (PKE) scheme is a cryptographic system that uses a pair of a public key and a corresponding private key. The security of PKE depends on maintaining the confidentiality of the private key. The public key can be publicly distributed, and anyone can encrypt using the public key that only the user who has the private key can decrypt it. The following is the syntax of PKE.

Definition 1 (PKE). *A PKE scheme consist of three algorithms* ***KeyGen****,* ***Encryption****,* ***Decryption*** *which are defined as follows:*

- ***KeyGen***(1^λ)*: The key generation algorithm takes as input a security parameter* 1^λ*. It outputs a public key* $\boldsymbol{pk}$ *and a private key* $\boldsymbol{sk}$*.*
- ***Encryption****(****pk****,* $\boldsymbol{M}$*):* *The encryption algorithm takes as input the public key* $\boldsymbol{pk}$ *and a message* $\boldsymbol{M} \in \mathcal{M}$*. It outputs a ciphertext* $\boldsymbol{c}$*.*
- ***Decryption****(****sk****,* $\boldsymbol{c}$*):* *The decryption algorithm takes as input the private key* $\boldsymbol{sk}$ *and the ciphertext* $\boldsymbol{c}$*. It outputs the message* $\boldsymbol{M}$ *or* $\perp$*.*

The correctness property of PKE is defined as follows: For all $\boldsymbol{pk}$ *and* $\boldsymbol{sk}$ *generated by* ***KeyGen***(1^λ)*,* $\boldsymbol{c}$ *generated by* ***Encryption****(****pk****,* $\boldsymbol{M}$*) for* $\boldsymbol{M}$*, it is required that*

- *If* $\boldsymbol{sk}$ *is valid, then* ***Decryption****(****sk****,* $\boldsymbol{c}$*)* $= \boldsymbol{M}$*.*
- *If* $\boldsymbol{sk}$ *is invalid, then* ***Decryption****(****sk****,* $\boldsymbol{c}$*)* $= \perp$*.*

2.2 Key Encapsulation Mechanism

A key encapsulation mechanism (KEM) is used to share the secret key of symmetric key encryption systems. The sender generates a ciphertext for sharing the secret key and sends it to the receiver. The receiver decapsulates the ciphertext and generates a secret key to be used for symmetric key encryption. The following is the syntax of KEM.

Definition 2 (KEM). *A KEM scheme consist of three algorithms* ***KeyGen****,* ***Encapsulation****,* ***Decapsulation*** *which are defined as follows:*

- ***KeyGen***(1^λ)*: The key generation algorithm takes as input a security parameter* 1^λ*. It outputs a public key* $\boldsymbol{pk}$ *and a private key* $\boldsymbol{sk}$*.*
- ***Encapsulation****(****pk****):* *The encapsulation algorithm takes as input the public key* $\boldsymbol{pk}$*. It outputs a ciphertext* $\boldsymbol{c}$ *and a shared key* $\boldsymbol{K}$*.*
- ***Decapsulation****(****sk****,* $\boldsymbol{c}$*):* *The decapsulaiton algorithm takes as input the private key* $\boldsymbol{sk}$ *and the ciphertext* $\boldsymbol{c}$*. It outputs the shared key* $\boldsymbol{K}$ *or* $\perp$*.*

The correctness property of KEM is defined as follows: For all $\boldsymbol{pk}$ *and* $\boldsymbol{sk}$ *generated by* ***KeyGen***(1^λ)*,* $\boldsymbol{c}$ *and* $\boldsymbol{K}$ *generated by* ***Encapsulation****(****pk****), it is required that*

- *If* $\boldsymbol{sk}$ *is valid, then* ***Decapsulation****(****sk****,* $\boldsymbol{c}$*)* $= \hat{\boldsymbol{K}}$ *such that* $\boldsymbol{K} = \hat{\boldsymbol{K}}$*.*
- *If* $\boldsymbol{sk}$ *is invalid, then* ***Decapsulation****(****sk****,* $\boldsymbol{c}$*)* $= \hat{\boldsymbol{K}}$ *or* $\perp$ *such that* $\boldsymbol{K} \neq \hat{\boldsymbol{K}}$*.*

2.3 Related Works

Lattice-based Public-Key Encryption. Due to the threat of quantum computers to the classical cryptography such as RSA or Diffie-Hellman, lattice-based cryptography is attracting attention as one of various post-quantum cryptography. The first lattice-based cryptographic construction was introduced by M. Ajtai [1]. And, the first lattice-based public key encryption (PKE) that called NTRU scheme is proposed by J. Hoffstein et al. [17]. The security of thier PKE scheme was not proven under worst-case hardness assumptions. In 2005, O. Regev [31] introduced the first lattice-based PKE scheme with the Learning With Errors (LWE) problem. The LWE problem is as difficult to solve as the worst-case lattice problems. Since then, a variety of lattice problems such as Learning With Rounding (LWR), Ring-LWE (RLWE), Ring-LWR (RLWR), etc. have been proposed [24,30,25,10], and these problems have been widely used to design public key cryptography. Also, after the process of standardizing post-quantum cryptography (PQC), many other lattice-based PKE schemes such as KYBER [8], NewHope [7], LAC [23], Round5 [9], Saber [15], and RLizard [22] assuming the hardness of lattice problems have been proposed.

CCA-secure KEM. Chosen-ciphertext attack (CCA) is a security model that allows an adversary to obtain the plaintext corresponding to the chosen ciphertext. Because the process of establishing a session key in communications is similar to accessing a decryption oracle by an adversary. It is very important to design the key encapsulation mechanism (KEM) considering the chosen-cipertext attack. Fujisaki and Okamoto [16] introduced a generic transformation method that can drive the chosen-cipertext secure KEM scheme from the chosen-plaintext secure PKE scheme. And, this method has been widely used to design many cryptographic algorithms. Recently, the Fujisaki-Okamoto transformation method in consideration of a quantum computing environment has been proposed [34,19,18]. Jiang et al. [19] presented Fujisaki-Okamoto transformation method that was proven tight security reductions in the quantum random oracle model.

3 Specification

3.1 Notation

In this subsection, we introduce some notations used in this document.
Let $\mathbb{Z}$ be the ring of rational integers. We define for an $x \in \mathbb{R}$ the rounding function $\lfloor x \rceil$, where $\lfloor x \rceil$ means the nearest integer to the x. We denote $R_q = \mathbb{Z}_q[X]/(X^n + 1)$ which means the ring of integer polynomial modulo $(X^n + 1)$, where each coefficient is reduced modulo q.
In this paper, n is a positive integer expressed as a power of two, which means the dimension of RLWE samples. q and p mean modulus for RLWE and RLWR, respectively. We also use the modulus k_i, where $i = 1, 2$, for ciphertext compression. We use p, q, k_1, and k_2 which are all the power of 2.

Bold lower-case letters represent polynomials with coefficients in R_q. Multiplication in R_q is represented by $*$. $\lfloor \mathbf{a} \rceil$ is the rounding to the nearest integer for each coefficient in the polynomial $\mathbf{a}$. $x \parallel y$ is the concatenation of x and y. $HWT_n\,(h, Seed)$ is the uniform distribution over the subset of $\{-1, 0, 1\}^n$ whose elements contain $n - h$ number of zeros, and is generated using $Seed$. $\texttt{SHAKE256}(m, len)$ is a hash function that receives m and outputs a byte-string of the length len. eccENC and eccDEC are functions for encoding and decoding using the error correction codes.

3.2 Specification of TiGER.CPAPKE

Algorithm 1 `IND-CPA.KeyGen`

Input: The set of public *parameters*
Output: Public key $pk = (Seed_a \parallel \mathbf{b})$, Private Key $sk = (\mathbf{s})$

$Seed_a \xleftarrow{\$} \{0,1\}^{256}$
$Seed_s \xleftarrow{\$} \{0,1\}^{256}$
$\mathbf{a} \leftarrow \texttt{SHAKE256}(Seed_a, n/8)$
$\mathbf{s} \leftarrow HWT_n(h_s, Seed_s)$
$\mathbf{b} \leftarrow \lfloor (p/q) \cdot \mathbf{a} * \mathbf{s} \rceil$
$pk \leftarrow (Seed_a \parallel \mathbf{b})$ and $sk \leftarrow \mathbf{s}$
return pk, sk

Algorithm 2 `IND-CPA.Encryption`

Input: pk, Message $\mathbf{M} \in \{0,1\}^d$; Coin $w \xleftarrow{\$} \{0,1\}^{256}$
Output: Ciphertext $\mathbf{c} = (\mathbf{c_1} \parallel \mathbf{c_2})$

$\mathbf{r} \leftarrow HWT_n(h_r, w)$
$Seed_{e1} \leftarrow (w + Nonce)$
$Seed_{e2} \leftarrow (w + Nonce + 1)$
$\mathbf{e_1} \leftarrow HWT_n(h_{e1}, Seed_{e1})$ and $\mathbf{e_2} \leftarrow HWT_n(h_{e2}, Seed_{e2})$
$Seed_a, \mathbf{b} \leftarrow \text{Parsing}(pk)$
$\mathbf{a} \leftarrow \texttt{SHAKE256}(Seed_a, n/8)$
$\mathbf{c_1} \leftarrow \lfloor (k_1/q) \cdot (\mathbf{a} * \mathbf{r} + \mathbf{e_1}) \rceil$
$\mathbf{c_2} \leftarrow \lfloor (k_2/q) \cdot ((q/2) \cdot \text{eccENC}(\mathbf{M}) + ((q/p) \cdot \mathbf{b}) * \mathbf{r} + \mathbf{e_2}) \rceil$
$\mathbf{c} \leftarrow (\mathbf{c_1} \parallel \mathbf{c_2})$
return $\mathbf{c}$

Algorithm 3 `IND-CPA.Decryption`

Input: sk, Ciphertext $\mathbf{c} = (\mathbf{c_1} \parallel \mathbf{c_2})$
Output: Message $\hat{\mathbf{M}}$

$\mathbf{c_1}, \mathbf{c_2} \leftarrow \text{Parsing}(\mathbf{c})$ and $\mathbf{s} \leftarrow sk$
$\hat{\mathbf{M}}' \leftarrow \lfloor (2/q) \cdot ((q/k_2) \cdot \mathbf{c_2} - ((q/k_1) \cdot \mathbf{c_1}) * \mathbf{s}) \rceil$
return $\hat{\mathbf{M}} \leftarrow \text{eccDEC}(\hat{\mathbf{M}}')$

3.3 Specification of TiGER.CCAKEM

We design IND-CCA KEM using the transformation technique by Jiang et al. [19]. We use a hash function $H : \{0,1\}^* \rightarrow \{0,1\}^{256}$, and a hash function $G : \{0,1\}^* \rightarrow \{0,1\}^*$ for Jiang's transformation technique.

Algorithm 4 `IND-CCA-KEM.KeyGen`

Input: The set of public *parameters*
Output: Public Key $pk = (Seed_a \parallel \mathbf{b})$, Private Key $sk = (sk_{cpa} \parallel \mathbf{u})$
1: $pk, sk_{cpa} :=$ `IND-CPA.KeyGen`$(parameters)$
2: $\mathbf{u} \xleftarrow{\$} R_2$
3: **return** $pk, sk \leftarrow (sk_{cpa} \parallel \mathbf{u})$

Algorithm 5 `IND-CCA-KEM.Encapsulation`

Input: pk
Output: Ciphertext $\mathbf{c} = (\mathbf{c_1} \parallel \mathbf{c_2})$, Shared Key $\mathbf{K}$
1: $\delta \xleftarrow{\$} \{0,1\}^d$
2: $\mathbf{c} :=$ `IND-CPA.Encryption`$(pk,\ \delta\ ;\ H(\delta, H(pk)))$
3: $\mathbf{K} \leftarrow G(H(\mathbf{c}),\ \delta)$
4: **return** $\mathbf{c}, \mathbf{K}$

Algorithm 6 `IND-CCA-KEM.Decapsulation`

Input: pk, sk, Ciphertext $\mathbf{c}$
Output: Shared Key $\mathbf{K}$
1: $\mathbf{s}, \mathbf{u} \leftarrow$ Parsing(sk)
2: $\hat{\delta} :=$ `IND-CPA.Decryption`$(\mathbf{s}, \mathbf{c})$
3: $\hat{\mathbf{c}} :=$ `IND-CPA.Encryption`$(pk,\ \hat{\delta}\ ;\ H(\hat{\delta}, H(pk)))$
4: **if** $\mathbf{c} = \hat{\mathbf{c}}$ **then** $\mathbf{K} \leftarrow G(H(\mathbf{c}), \hat{\delta})$ **else** $\mathbf{K} \leftarrow G(H(\mathbf{c}), \mathbf{u})$
5: **return** $\mathbf{K}$

3.4 Parameter sets

We construct a TiGER128 that satisfies security level 1 (AES128), a TiGER192 that satisfies security level 3 (AES192) and TiGER256 that satisfies security level 5 (AES256) as required by the NIST standardization process. Table 1 shows the detailed parameters of each security level and the bandwidth according to each security level is summarized in Table 2.

n is the dimension of the lattice, q is the modulus of RLWE, p is the modulus of RLWR, k_1 and k_2 are the modulus used for ciphertext compression, h is the hamming weight of the secret key and the ephemeral secret used to encryption. h_{e_1} and h_{e_2} are the hamming weight of the encryption. d is the length of the message, which is related to the security level. f is the number of error bits fixed by error correcting code. Bandwidth is a sum of ciphertext and public key size.

Table 1: The detail parameters for each security level

parameters	n	q	p	k_1	k_2	h_s	h_r	h_{e1}	h_{e2}	d	f
TiGER128	512	256	128	128	8	104	104	32	32	128	3
TiGER192	1024	256	128	128	8	116	116	32	32	256	5
TiGER256	1024	256	128	256	8	184	184	256	32	256	5

Table 2: Size of pk, sk, and ciphertext (bytes)

parameters	Ciphertext	Public key	Secret key*
TiGER128	640	480	134
TiGER192	1,280	928	178
TiGER256	1,408	928	263

* sk_{cpa} can be encoded by storing only non-zero indexes. Thus, we adopted sk can be compressed with $encoding(sk_{cpa})$, a flag of 1 or -1, and $\mathbf{u}$ (for IND-CCA KEM).

3.5 Correctness

The following shows the correctness of our PKE scheme. Let $\hat{\mathbf{M}}$ be an encoded message from eccENC ($\mathbf{M}$), where $\mathbf{M} \in \mathcal{M}$. Let ψ be a positive integer parameter and $\mathbf{s}$, $\mathbf{r}$, $\mathbf{e_1}$, $\mathbf{e_2}$ are randomly chosen from a same distribution $\mathcal{D}$. The value of $\mathbf{e_b}$ is :

$$\mathbf{e_b} = ((\frac{q}{p}) \cdot \lfloor (\frac{p}{q}) \cdot \mathbf{b} \rceil) - \mathbf{b},$$

for some $\mathbf{e_b} \in R_\psi$. The value of $\mathbf{e_{c_1}}$ is :

$$\mathbf{e_{c_1}} = ((\frac{q}{k_1}) \cdot \lfloor (\frac{k_1}{q}) \cdot \mathbf{c_1} \rceil) - \mathbf{c_1},$$

for some $\mathbf{c_1} \in R_\psi$. The value of $\mathbf{e_{c_2}}$ is :

$$\mathbf{e_{c_2}} = ((\frac{q}{k_2}) \cdot \lfloor (\frac{k_2}{q}) \cdot \mathbf{c_2} \rceil) - \mathbf{c_2},$$

for some $\mathbf{c_2} \in R_\psi$. Then, the decryption process is as follows:

$$\begin{aligned}
&\lfloor (\frac{2}{q}) \cdot \big(((\frac{q}{k_2}) \cdot \mathbf{c_2} - ((\frac{q}{k_1}) \cdot \mathbf{c_1}) * \mathbf{s} \big) \rceil \\
=&\lfloor (\frac{2}{q}) \cdot \big(((\frac{q}{k_2}) \cdot \lfloor (\frac{k_2}{q}) \cdot ((\frac{q}{2}) \cdot \hat{\mathbf{M}} + ((\frac{q}{p}) \cdot \lfloor (\frac{p}{q}) \cdot \mathbf{a} * \mathbf{s} \rceil) * \mathbf{r} + \mathbf{e_2}) \rceil \\
&- ((\frac{q}{k_1}) \cdot \lfloor (\frac{k_1}{q}) \cdot (\mathbf{a} * \mathbf{r} + \mathbf{e_1}) \rceil) * \mathbf{s} \big) \rceil \\
=&\lfloor (\frac{2}{q}) \cdot \big((((\frac{q}{2}) \cdot \hat{\mathbf{M}} + \mathbf{e'_b}\mathbf{r} + \mathbf{e'_2} + \mathbf{e_{c_2}}) - (\mathbf{e'_1}\mathbf{s} + \mathbf{e_{c_1}}\mathbf{s}) \big) \rceil \\
=&\hat{\mathbf{M}},
\end{aligned}$$

Let $\mathbf{f} = (\mathbf{e'_b r} + \mathbf{e'_2} + \mathbf{e_{c_2}}) - (\mathbf{e'_1 s} + \mathbf{e_{c_1} s})$, We have that the error rate is $\hat{\epsilon} = 1 - Pr[\lfloor -q/2 \rceil < \mathbf{f_i} + \mathbf{f_j} < \lfloor q/2 \rceil]$, since our PKE scheme uses D2 encode that encodes from one message bit to two coefficients. Using the decryption failure rate estimator of M. Albrecht[2], we obtain that the error rate of each message bit is $2^{-42.06}$. Our PKE scheme uses XE3 in security level 1 to correct 3-bit errors, we have that

$$\epsilon = 1 - \Big(\sum_{f=0}^{3} \binom{512}{f} \cdot ((2^{-42.06})^f) \cdot (1 - 2^{-42.06})^{512-f} \Big) \approx 2^{-136.86}.$$

Then, our PKE scheme is (1-ϵ)-correct with $\epsilon < 2^{-128}$, where security parameter λ is 128. The following Table 3 shows the decryption failure rate of our PKE scheme's each parameters. Note that there is a hidden margin in our decryption failure rate calculation. XEf accurately corrects errors of f-bits and can correct errors more than f with a high probability. Experimentally XE5 corrects 99.4% of random 6-bit errors and 97.0% of random 7-bit errors[32].

Table 3: Decryption failure rate

parameters	Bit error rate	Decryption failure rate	f^*
TiGER128	$2^{-42.06}$	$2^{-136.86}$	3
TiGER192	$2^{-39.60}$	$2^{-187.10}$	5
TiGER256	$2^{-35.62}$	$2^{-163.21}$	5

* Let f be the bit length to be corrected by using the XEf.

4 Performance analysis

4.1 Description of platform

We evaluate performance (CPU cycles) using each reference code, and the evaluation environment is AMD Ryzen7 5700G @3.8GHz CPU, Ubuntu 22.04.1, GCC 11.3.0 with option −O3, and the value is the average for 10,000 iterations. Also, our implementation is available to https://github.com/honggoonin/TIGER.git.

4.2 Performance of reference implementation

TiGER is 1.3-3.0 times faster than the KYBER reference implementation[3] and 1.09-2.02 times faster than the SMAUG[12] reference implementation[4], with an equivalent security level. In particular, the higher the security strength, the larger the difference in performance between the TiGER and KYBER, SMAUG. KYBER supports

[2] https://bitbucket.org/malb/lwe-decryption-failure.git
[3] https://github.com/pq-crystals/kyber.git
[4] https://github.com/kpqc-cryptocraft/KPQClean

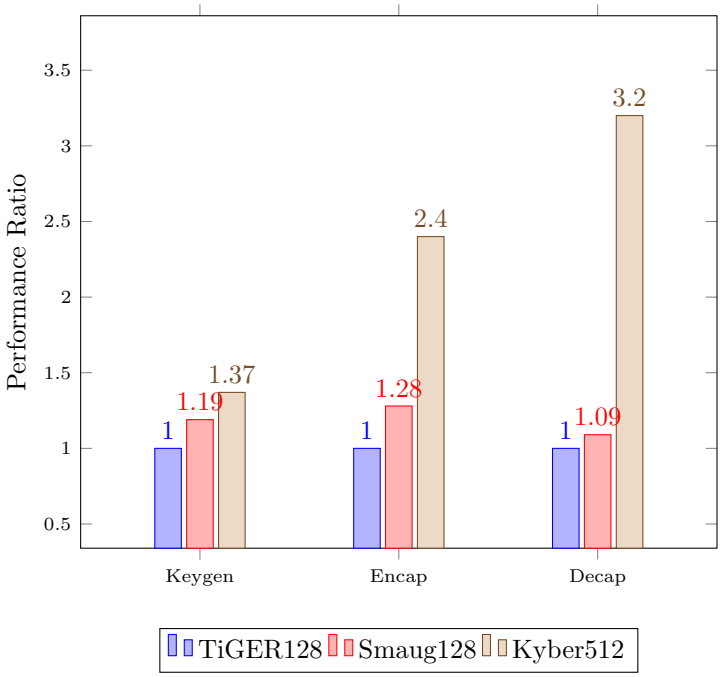
algorithms with 128, 192, and 256 security. But, considering that only 256-bit security was adopted in CNSA(Commercial National Security Algorithm Suite) 2.0 in NSA, a base applied in real environments, the performance of TiGER256 is superior to the other two algorithms.

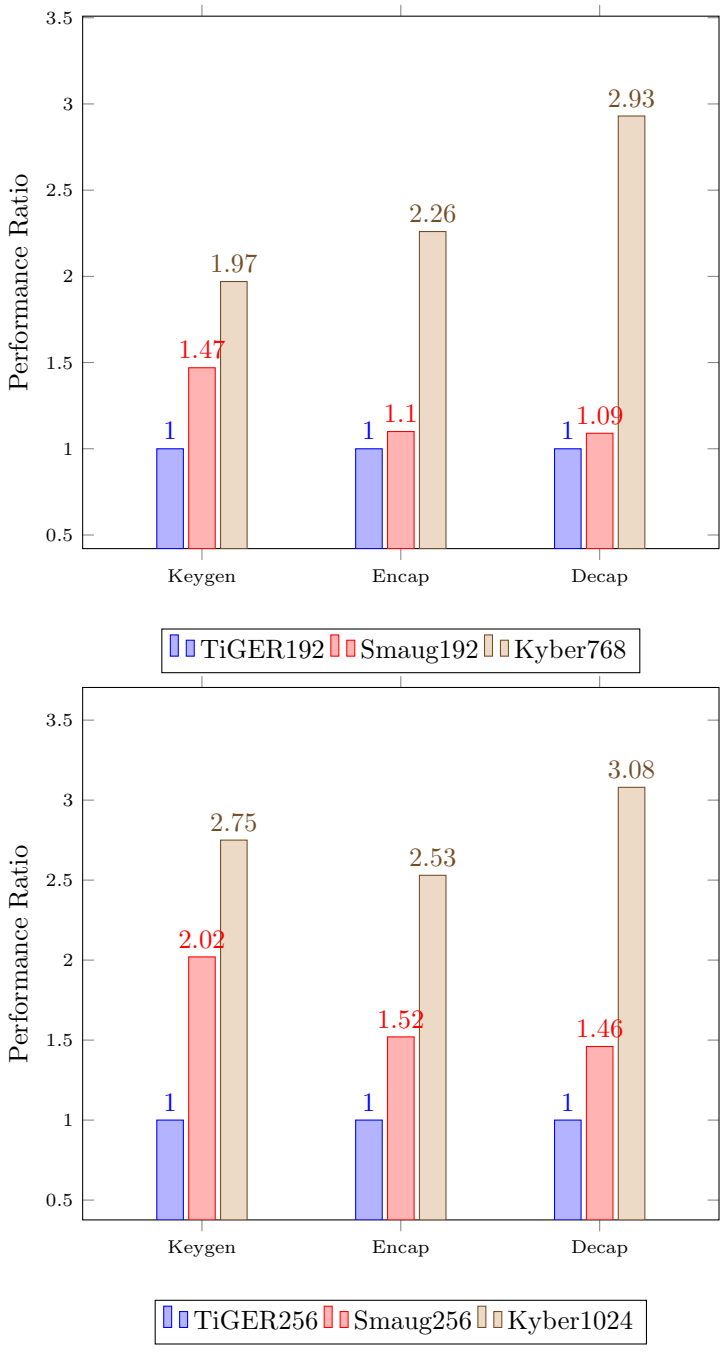
This result is an advantage of our scheme's design by choosing q in bytes to the power of 2 and sampling the secret from a sparse ternary uniform distribution. The performance overhead of `XEf` and `D2` is not heavy.

In addition, a recent study showed the application of NTT through modulus switching in the NTT unfriendly parameter where the modulus q is a power of 2, improving Saber by 25-61% and LAC by 2-4 times [14]. Studies like this will have a positive impact on our schemes as well.

Table 4: Performance (CPU cycles)

Algorithm	Key generate	Encapsulation	Decapsulation
TiGER128	66,943	49,655	46,223
TiGER192	78,344	81,446	75,432
TiGER256	85,593	105,057	101,303
Kyber512	91,936	119,371	148,105
Kyber768	154,260	183,846	221,243
Kyber1024	235,419	265,678	311,882
Smaug128	79,467	63,588	50,367
Smaug192	114,961	89,745	82,542
Smaug256	172,480	160,111	148,003




Performance Ratio
3.5
3
2.5
2
1.5
1
0.5
1
1.47
1.97
1
1.1
2.26
1
1.09
2.93
Keygen
Encap
Decap
TiGER192
Smaug192
Kyber768
Performance Ratio
3.5
3
2.5
2
1.5
1
0.5
1
2.02
2.75
1
1.52
2.53
1
1.46
3.08
Keygen
Encap
Decap
TiGER256
Smaug256
Kyber1024

5 Security

5.1 Security definition

The following is the formal definition of the IND-CPA security.

Definition 3 (IND-CPA). *Let* $\mathsf{PKE} = (\boldsymbol{KeyGen}, \boldsymbol{Encrypt}, \boldsymbol{Decrypt})$ *be a public-key encryption scheme. The security of PKE under chosen plaintext attacks is defined in terms of the following experiment between a challenger* $\mathcal{C}$ *and an adversary* $\mathcal{A}$*:*

$\boldsymbol{Exp}^{IND\text{-}CPA}_{PKE,\mathcal{A}}(\lambda)$

1. $(pk, sk) \leftarrow \boldsymbol{KeyGen}(1^\lambda)$;
2. $(M_0, M_1) \leftarrow \mathcal{A}$;
3. $\mathcal{C}$ *flips a random coin* $b \in \{0, 1\}$;
4. $ct \leftarrow \boldsymbol{Encrypt}(PK, M_b)$;
5. $b' \leftarrow \mathcal{A}$;

   If $b = b'$, *return 1.*

   Otherwise, return 0.

The advantage of $\mathcal{A}$ is defined as $\mathbf{Adv}^{IND\text{-}CPA}_{PKE,\mathcal{A}}(\lambda) = \left| \Pr[b = b'] - \frac{1}{2} \right|$ where the probability is taken over all the randomness of the experiment. A PKE scheme is secure in the security model under chosen plaintext attacks if for all adversary $\mathcal{A}$, the advantage of $\mathcal{A}$ in the above experiment is negligible in the security parameter λ.

5.1.1 Security Assumption We define decisional Ring Learning With Errors (RLWE) problem and decisional Ring Learning With Rounding (RLWR) problem. Let R_q, R_p denote the rings $\mathbb{Z}_q[x]/(g(x))$, $\mathbb{Z}_p[x]/(g(x))$, where $g(x)$ is an irreducible polynomial of degree n.

Definition 4 (decisional RLWE). *Let* n, q *be positive integers. Let* R_q *be polynomial ring constructed by* $g(x)$*, and let* $\mathfrak{D}_s$ *be a distribution over* R_q*. A decisional RLWE problem* $\mathbf{RLWE}_{n,q}(\mathfrak{D}_s)$ *is to distinguish uniformly random* $(\mathbf{a}, \mathbf{u}) \in R_q \times R_q$ *and* $(\mathbf{a}, \mathbf{b} = \mathbf{a} * \mathbf{s} + \mathbf{e}) \in R_q \times R_q$*, where* $\mathbf{a}$ *is uniform randomly chosen polynomial,* $\mathbf{e}$ *is chosen from error distribution, and* $\mathbf{s}$ *is a secret polynomial. Then, the advantage of an adversary* $\mathcal{A}$ *in solving the decisional RLWE problem* $\mathbf{RLWE}_{n,q}(\mathfrak{D}_s)$ *is defined as follows:*

$$\boldsymbol{Adv}^{RLWE}_{n,q}(\mathcal{A}) = |\mathsf{Pr}[\mathcal{A}(\mathbf{a}, \mathbf{b}) = 1] - \mathsf{Pr}[\mathcal{A}(\mathbf{a}, \mathbf{u}) = 1]|.$$

Definition 5 (decisional RLWR). *Let n, q, p be positive integers such that $q > p$. Let R_q, R_p be polynomial rings constructed by $g(x)$, and let $\mathfrak{D}_s$ be a distribution over R_q. A decisional RLWR problem $\mathbf{RLWR}_{n,q,p}(\mathfrak{D}_s)$ is to distinguish uniformly random $(\mathbf{a}, \mathbf{u}) \in R_q \times R_p$ and $(\mathbf{a}, \mathbf{b} = \lfloor (p/q) \cdot (\mathbf{a} * \mathbf{s}) \rceil) \in R_q \times R_p$, where $\mathbf{a}$ is uniform randomly chosen polynomial, and $\mathbf{s}$ is a secret polynomial. Then. the advantage of an adversary $\mathcal{A}$ in solving the decisional RLWR problem $\mathbf{RLWR}_{n,q,p}(\mathfrak{D}_s)$ is defined as follows:*

$$\boldsymbol{Adv}^{RLWR}_{n,q,p}(\mathcal{A}) = |\mathsf{Pr}[\mathcal{A}(\mathbf{a}, \mathbf{b}) = 1] - \mathsf{Pr}[\mathcal{A}(\mathbf{a}, \mathbf{u}) = 1]|.$$

5.2 Formal Security

5.2.1 Security of IND-CPA PKE We prove that our PKE scheme is IND-CPA secure under the RLWE assumption and the RLWR assumption.

Theorem 1 (IND-CPA PKE). *The above PKE scheme is secure under chosen plaintext attacks if the the RLWE assumption and the RLWR assumption holds. That is, for any PPT adversary $\mathcal{A}$, we have that $\boldsymbol{Adv}^{IND-CPA}_{PKE}(\mathcal{A}) \leq \boldsymbol{Adv}^{RLWE}_{n,q}(\mathcal{B}) + \boldsymbol{Adv}^{RLWR}_{n,q,p}(\mathcal{B})$.*

Proof. The security proof consists of the sequence of hybrid games: The first game will be the original security game and the last one will be a game such that the adversary has no advantage. Let $\hat{\mathbf{M}} = \text{eccENC}(\mathbf{M})$. We define the games as follows:

Game G_0 **:** This game is the original security game. In this game, the public key and the ciphertext are properly generated. $\mathcal{D}_0$ is described as follows:

$$\mathcal{D}_0 = \{pk = (Seed_a \parallel \mathbf{b} = \lfloor (\frac{p}{q}) \cdot \mathbf{a} * \mathbf{s} \rceil),$$
$$ct = (\lfloor (\frac{k_1}{q}) \cdot (\mathbf{a} * \mathbf{r} + \mathbf{e_1}) \rceil), \lfloor (\frac{k_2}{q}) \cdot ((\frac{q}{2}) \cdot \hat{\mathbf{M}}_b + ((\frac{q}{p}) \cdot \mathbf{b}) * \mathbf{r} + \mathbf{e_2}) \rceil\}.$$

Game G_1 **:** In the next game, $\mathbf{b}$ in the public key is replaced with uniformly random polynomial in R_p.$\mathcal{D}_1$ is described as follows:

$$\mathcal{D}_1 = \{pk = (Seed_a \parallel \mathbf{b} \xleftarrow{\$} R_p),$$
$$ct = (\lfloor (\frac{k_1}{q}) \cdot (\mathbf{a} * \mathbf{r} + \mathbf{e_1}) \rceil), \lfloor (\frac{k_2}{q}) \cdot ((\frac{q}{2}) \cdot \hat{\mathbf{M}}_b + ((\frac{q}{p}) \cdot \mathbf{b}) * \mathbf{r} + \mathbf{e_2}) \rceil\}.$$

Therefore, |Pr[S_0] - Pr[S_1]| $\leq \mathbf{Adv}^{RLWR}_{n,q,p}(\mathcal{B})$.

Game G_2 **:** In the final game, $\mathbf{a} * \mathbf{r} + \mathbf{e_1}$ and $(q/p) \cdot \mathbf{b}) * \mathbf{r} + \mathbf{e_2}$ are replaced with uniformly random polynomial in R_q. Let $\mathbf{u} \xleftarrow{\$} R_q$ and $\mathbf{v} \xleftarrow{\$} R_q$. $\mathcal{D}_2$ is described

as follows:

$$\mathcal{D}_2 = \{pk = (Seed_a \parallel \mathbf{b} \xleftarrow{\$} R_p),$$
$$ct = (\lfloor(\frac{k_1}{q}) \cdot \mathbf{u}\rceil), \lfloor(\frac{k_2}{q}) \cdot ((\frac{q}{2}) \cdot \hat{\mathbf{M}}_b + \mathbf{v})\rceil\}.$$

Therefore, |Pr[S_1] - Pr[S_2]| $\leq \mathbf{Adv}^{RLWE}_{n,q}(\mathcal{B})$.

It follows that

$$\mathbf{Adv}^{IND-CPA}_{PKE}(\mathcal{A}) = |Pr[S_0] - Pr[S_2]| \leq |Pr[S_0] - Pr[S_1]| + |Pr[S_1] - Pr[S_2]|$$
$$\leq \mathbf{Adv}^{RLWE}_{n,q}(\mathcal{B}) + \mathbf{Adv}^{RLWR}_{n,q,p}(\mathcal{B}),$$

which concludes the proof of Theorem 1.

5.2.2 Security of IND-CCA KEM We prove that our KEM scheme is IND-CCA secure under the public-key encryption in the quantum random oracle. Using Theorems 1 of Jiang et al. [19], we get the Theorem 2 for the IND-CCA security of our KEM in the quantum random oracle model.

Theorem 2 (IND-CCA KEM in QROM). *We define a public key encryption scheme PKE = (KeyGen, Encrypt, Decrypt) with message space $\mathcal{M}$ and which is (1-ϵ)-correct. For any IND-CCA quantum adversary $\mathcal{A}$ that makes at most q_D queries to the decryption oracle, at most q_G queries to the random oracle G and at most q_H queries to the random oracle H, we have that*

$$\boldsymbol{Adv}^{IND-CCA}_{KEM}(\mathcal{A}) \leq 2q_H\frac{1}{\mathcal{M}} + 4q_G\sqrt{1-\epsilon} + 2(q_G + q_H)\sqrt{\boldsymbol{Adv}^{IND-CPA}_{PKE}(\mathcal{B})}.$$

5.3 Security strength categories

TiGER128, TiGER192, and TiGER256 achieve the security-levels 1, 3, and 5 suggested by the NIST [3], respectively, and the expected security strength for each parameter set is shown in Table **??**. The expected security strength is based on MATZOV [26] and was estimated by `LATTICE-ESTIMATOR` [5]. In addition, we considered the combinatorial attack [27].

5.4 Cost of known attacks

We estimate the security strength of RLWR and RLWE, respectively, due to the character of the TiGER scheme, which uses a combination of RLWR for key generation and RLWE for encryption. The RLWR security strength estimate is equivalent to the LWE, whose noise distribution is uniform over the integers in the range $[-q/2p, q/2p)$ [11]. Estimating the security strength of ciphertext additionally considers deterministic noise added due to ciphertext compression in RLWE. For example, if q is 2^8 and k_1 compressing ciphertext $\mathbf{c_1}$ is 2^6, a

Table 5: Computational complexity of best known attacks

Parameter set	TiGER128	TiGER192	TiGER256
Target security	I	III	V
quantum Core-SVP	119	210	242
classic Core-SVP	127	221	257
MATZOV	145	235	273
Meet-LWE	(time) 144 (mem) 123	(time) 207 (mem) 182	(time) 291 (mem) 250

uniform distribution noise (c_{1e}) in the integer range of at least $[-1, 1]$ is added (stdev = 0.82) . If noise e_1 of RLWE generates $HWT(1024, 168)$, the standard deviation is 0.29, so the standard deviation of the final noise is $e_1 + c_{1e} = 0.86$.

We estimate the security strength based on two cost-reduction models. First, our estimates are based on the classical and the quantum Core-SVP hardness [7], which is a very conservative underestimation of the real security. Core-SVP is most commonly used in NIST competition, making it easy to compare algorithms. It also allows for a conservative approach in a quantum environment. The conservative estimation of classical Core-SVP is challenging to compare with the number of gates. For example, `KYBER512` claims that the classical security strength 2^{118} based on Core-SVP can be converted to a classical gate of $2^{151.5}$ [8], and `Light-SABER` also claims that the computational complexity of 2^{118} is converted into 2^{144} [15]. On the other hand, MATZOV [26] reported that classical gates are stricter than their estimates, `KYBER512` has a security strength of $2^{137.5}$, and `Light-SABER` has a security strength of $2^{138.4}$, which does not satisfy the security level. Although a script replicating MATZOV's results has not been released, Albrecht et al. implemented it in `LATTICE-ESTIMATOR` [5], estimating the security strength as 2^{140} for `KYBER512` and $2^{137.8}$ for `Light SABER`, supporting MATZOV's result. Therefore, we present classical cost with Albrecht et al.'s estimator [5] that implements MATZOV, the state-of-the-art security strength estimation method.

As shown in Table 5, TiGER128, TiGER192, and TiGER256 exceed the classical security strengths of 2^{143}, 2^{207}, and 2^{272} suggested by NIST, respectively. In addition, the classical Core-SVP estimate has a security strength margin of 2^9, 2^{38}, and 2^1 compared to `Kyber`, corresponding to each security level.

In a quantum environment, the impact of MAXDEPTH is a major factor in estimating security strength. NIST has described a plausible value range for MAXDEPTH from 2^{40} logical gates to 2^{64} logical gates [33]. `Kyber` claims that for the core-SVP-hardness operation estimates to match the quantum gate cost of breaking AES at the respective security levels, a quantum computer would need to support a maximum depth of 2^{70-80} [8]. The TiGER security strength estimates in quantum Core-SVP are sufficient considering the lower limit of the range of MAXDEPTH suggested by NIST. Also, TiGER has 2^{12}, 2^{44}, and 2^{10} higher than `Kyber` with the same security level, respectively. Remark, We report all security strength estimated by the `LATTICE-ESTIMATOR` [5].

As our scheme is based on the RLWE(R) designed by sparse ternary distributions with Hamming weights, it is weak against the combinatorial attack by May [27]. By May analyzed that time complexity is roughly $S^{0.3}$, and the memory requirement of this attack is roughly $S^{0.25}$, where S is the space of the secret key. We estimate the security using the Meet-LWE python code by the SMAUG team[5].

6 Summary

The PQC-KEM design aims to replace cryptography in legacy security protocols. It would be nice if PQC-KEM had better performance and bandwidth than ECDH or DH for easy migration, but it seems impossible. Therefore, the maximum range of performance and bandwidth acceptable to the security protocol and network environment should be carefully considered and determined as the threshold of the scheme design. We decided the bandwidth threshold to be 1,500 bytes based on the ethernet MTU.

In this paper, we propose TiGER, an IND-CCA secure KEM based on RLWE(R). We design schemes with ciphertext and public key sizes smaller than 1,500 bytes each to simplify migration to the current network. More precisely, TiGER256 with AES256 security level has 1,408 bytes of ciphertext and 928 bytes of public key. A bandwidth smaller than the MTU is advantageous for immigration because it prevents fragmentation in security protocols. Small ciphertext and public key size were achieved by choosing RLWR and RLWE as the base hardness, compressing the ciphertext, and choosing a small modulus $q = 256$. It is also 1.3-3.0 times faster than the reference implementation of KYBER, NIST's first standard KEM. It is the advantage of choosing a sparse ternary uniform distribution. TiGER128, TiGER192, and TiGER256 satisfy security levels 1, 3, and 5, respectively, based on MATZOV, Core-SVP, and Meet-LWE attack. The high decoding failure rate of the TiGER design achieved a negligible decryption failure probability by correcting errors using XEf and D2 encoding.

In the future, TiGER is expected to achieve good results in the KpqC competition through additional study on the side-channel analysis, optimal implementation, and more efficient attacks.

[5] https://kpqc.cryptolab.co.kr/smaug

7 Change Log

2022.12.8. (v1.1)

The bit error rate values in Table 3 have been changed. In TiGER (v1.0 for the Kpqc Competition Draft), We entered the Decryption Failure Rate (DFR) without an error-correcting code. However, To obtain the final DFR (with error-correcting code), First, The bit error rate is obtained from the DFR without error-correcting code; Second, the bit error rate was used to calculate the final DFR. The final result(DFR) has not changed, but we acknowledge our mistake. We thank Hyeongmin.Choe, a researcher at Seoul National University, for helpful comments.

2023.2.16. (v2.0)

1. We changed Table 1 because it improved our scheme for D. J. Bernstein's invaluable comment about combinatorial lattice security on the Kpqc bulletin. Table 1 is the parameter set for our scheme. Therefore, Table 2 to Table **??** also change. But, TiGER still satisfied each security level, has negligible decryption failed rate, and has tiny bandwidth and efficient performance.

2. To prevent multi-target attacks, we add $H(pk)$ to the input coin for encryption in algorithm 5 and algorithm 6. Also, input $H(\mathbf{c})$ instead of the ciphertext $\mathbf{c}$ in an algorithm 6 for generating the shared key.

3. Slightly optimized the reference implementation. The first is a modification for the constant-time implementation in step 4 of algorithm 6, a well-known side-channel attack surface. In other words, the implementation that checks whether $\mathbf{c}$ and $\hat{\mathbf{c}}$ are the same modified by referring to FrodoKEM [6]. The second is to improve polynomial multiplication and the sparse ternary sampling with hamming-weight, which have a relatively large overhead. The basic idea of polynomial multiplication is to turn it into a simple operation that produces 2's complement instead of multiplying by -1. The sparse ternary sampling with hamming-weight followed the thesis [21]. It improved performance by 10-19%.

2023.7.16. (v2.1)

1. Resolved an issue whereby the sizes of the ciphertext and public key did not align between our official specification document (v2.0, 2023.02.21.) and the reference implementation. The problem arose due to a data type discrepancy when storing the passphrase and public key in our reference implementation. We have uploaded a new reference implementation to the official website https://github.com/honggoonin/TIGER.git as a solution.

2. The storage method for the **sk** index, as sketched in our official specification document (v2.0), has been changed to the default setting. This change has significantly reduced the size of the private key and simplified the decapsulation operation. Moving forward, **sk** will only store the index where -1 and 1 are located, along with the *negstart* variable, representing the point where the values of -1 and 1 change.

3. During the 6th KPQC workshop (2023.07.14.), Hee-Seok Kim has several side-channel analysis vulnerabilities. We mitigate it. Firstly, we eliminated the

conditional statement from the HWT function and implemented it as a constant time operation. Additionally, we addressed the vulnerability related to power analysis caused by differences in the Hamming weight of the mask variable in the `D2` encoding process. The updated reference implementation has also been uploaded to the official website.

4. The enhanced reference implementation was modified based on the KPQClean project[6] by Hwa-jeong Seo. As a result, the code available on the official website can be directly compared with other algorithms implemented in the KPQClean project.

2023.9.11. (v3.0) An error in the decryption failure probability calculation formula has been corrected. Because of this, the parameters have been changed, but it still has good performance and small ciphertext and key size. We have uploaded a new reference implementation to the official website https://github.com/honggoonin/TIGER.git. We thank Seungwoo Lee, a researcher at Korea University, for his helpful comments.

[6] https://github.com/kpqc-cryptocraft/KPQClean

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